GAMMA-RAY LINE EMISSION FROM ^{7}LI AND ^{7}BE PRODUCTION BY COSMIC-RAYS

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ABSTRACT

We calculate the total γ-ray line emission at $\sim$450 keV that accompanies ^{7}Li and ^{7}Be production by cosmic-ray interactions, including the delayed line emission at 0.478 MeV from ^{7}Be radioactive decay. We present a new γ-ray spectroscopic test which has the potential to give direct information on the nature of the interstellar regions into which ^{7}Be ions propagate and decay. Finally, we evaluate the intensity of the predicted diffuse emission from the central radian of the Galaxy.

Key words: Cosmic-rays; Light Elements; Gamma-rays; Spectroscopy.

1. INTRODUCTION

Although it has been known for three decades that cosmic-ray spallation is important to the origin of the light elements Li, Be and B, neither the sources of the cosmic-rays nor their interactions with the interstellar medium are yet well understood (see Vangioni-Flam et al., 2000, for a recent review). Future observations with INTEGRAL of the nuclear γ-ray line emission that accompanies the light element production could shed new light on this non-thermal nucleosynthesis. The γ-ray line emission at $\sim$450 keV from ^{7}Li and ^{7}Be production is often detected in solar flares and could be important in the interstellar medium as well. Its intensity and profile are evaluated in Ramaty et al. (1979) and references therein. In this paper, we supplement the work of these authors with detailed calculations of the delayed line emission at 0.478 MeV that follows the radioactive decay of ^{7}Be to the first excited state of ^{7}Li.

2. ^{7}BE PRODUCTION

We considered a steady state, thick target model (e.g. Ramaty et al., 1996) in which ^{7}Be is produced by nuclear interactions of accelerated ions with a neutral ambient medium of solar composition. We employed an ion source spectrum resulting from shock acceleration (e.g. Ramaty et al., 1997)

$$\dot{Q}_i(E_i) \propto \frac{p_i^{-s}}{\beta_i}\exp(-E_i/E_0) \tag{1}$$

where p_i, $c\beta_i$ and E_i are, respectively, the momentum, velocity and kinetic energy per nucleon of the accelerated particle of type i, and E_0 is a high-energy cutoff. We used s=2, which applies to strong shocks. We considered two different compositions for the fast ions: the composition of the current epoch Galactic cosmic-ray sources (CRS; Ramaty et al., 1997) and the average composition of the stellar winds and supernova ejecta from OB associations in the inner Galaxy (OB$_{\rm IG}$; Parizot et al., 1997).

The total cross section for the reaction ^{4}He(α,n)^{7}Be is from the data compilation of Read & Viola (1984), with the corrections suggested by Mercer et al. (1997) to the data of Glagola et al. (1982). The total cross sections for the CNO spallation reactions by protons and α-particles are also based on Read & Viola (1984), but we supplemented the data compilation of these authors with the data of Epherre & Seide (1971) for the ^{14}N(p,X)^{7}Be reaction, and of Lafleur et al. (1966) and Inoue & Tanaka (1976) for the ^{16}O(p,X)^{7}Be reaction. We see from Figure 1 that the α+α reaction is the main source of ^{7}Be for E_0 < 100 MeV/nucleon. We show in §4 that such low values of E_0 provide the most favourable cases for observing the predicted γ-ray line emission with INTEGRAL. We therefore concentrate in this paper on the γ-ray line production by α+α reactions.

The differential cross section for the production of ^{7}Be with recoil energy E_7 can be written as

$$\frac{d\sigma^*_{\alpha\alpha}}{dE_7}(E_\alpha,E_7) = \sigma^*_{\alpha\alpha}(E_\alpha)\cdot\frac{dW^*_{\alpha\alpha}}{d\theta_7^{cm}}(E_\alpha,\theta_7^{cm})\cdot\frac{d\theta_7^{cm}}{dE_7}\ , \tag{2}$$

where $\sigma^*_{\alpha\alpha}(E_\alpha)$ is the total cross section for the reaction ^{4}He(α,n)^{7}Be, $d\theta_7^{cm}/dE_7$ is a kinematic factor and $dW^*_{\alpha\alpha}/d\theta_7^{cm}$ is the center-of-mass angular distribution of the recoil nuclei, for which we adopted the energy-dependent analytical formula derived by

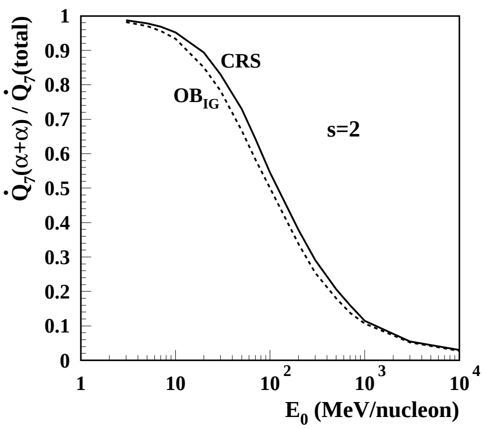

Figure 1. Ratio of the ^7Be production rate from the $^4He(\alpha,n)^7Be$ reaction to the total ^7Be production rate, as a function of E_0 (Eq. 1).

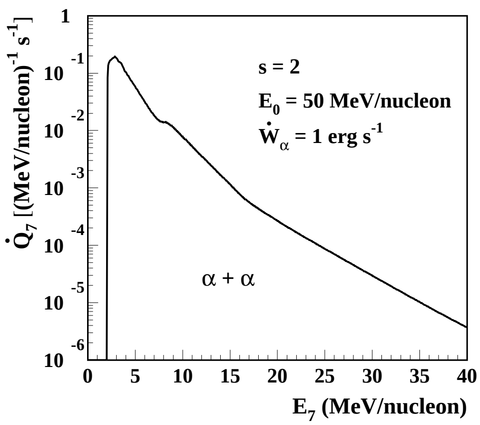

Figure 2. Thick target differential ^7Be production rate for the reaction $^4He(\alpha,n)^7Be$ and the α-particle source spectrum of Eq. (1) with s=2 and E_0=50 MeV/nucleon. The calculation is normalized such that the instantaneous energy deposition rate by the accelerated α-particles is 1 erg/s. The energy cut-off at $E_7 \simeq 2$ MeV/nucleon is due to the reaction kinematics.

Murphy et al. (1988) from available experimental data. We show in Figure 2 calculated energy distribution of ^{7}Be ions produced by the ^{4}He(α,n)^{7}Be reaction.

3. GAMMA-RAY LINE EMISSION FROM ^{7}BE DECAY

^{7}Be is a radioisotope which decays by nuclear electron capture only, with a measured half-life for atoms $\tau_{1/2}$=53.29 days (Ajzenberg-Selove, 1988). It decays with 10.35 % probability to the first excited state of ^{7}Li, thus producing γ-ray line emission at 0.478 MeV. The decay rate depends on the ^{7}Be atomic charge and a fully ionized ion can only decay by highly improbable nuclear electron capture from continuum states. Thus, its half-life in the interstellar medium is very long, $\tau_{1/2}^{(0)} \gtrsim 10^{20}$ years (see Bahcall, 1962, eq. 20), so that it is stable as compared with the age of the Universe. The decay rates, $\lambda^{(n)}$, for ^{7}Be ions with n bound electrons are given by

$$\lambda^{(4)} = \frac{\ln 2}{\tau_{1/2}} = \lambda_K + \lambda_L = \lambda_K(1+f_{LK}) \quad (3)$$

$$\lambda^{(3)} = \frac{\lambda^{(4)}}{1+f_{LK}}\left(1+\frac{f_{LK}}{2}\right)\left(\frac{Z-2c_K{}'}{Z-c_L-2c_K{}'}\right)^2 \quad (4)$$

$$\lambda^{(2)} = \frac{\lambda^{(4)}}{1+f_{LK}} \quad (5)$$

$$\lambda^{(1)} = \frac{\lambda^{(4)}}{2(1+f_{LK})}\left(\frac{Z}{Z-c_K}\right)^2 . \quad (6)$$

Here λ_K and λ_L are the decay rates from the two 1s and the two 2s electrons, respectively; f_{LK}=λ_L/λ_K=3.31 % (Hartree & Hartree, 1935); Z=4 is the ^{7}Be nuclear charge; and the shielding constants c_K=0.3, $c_K{}'$=0.85 and c_L=0.35 (Slater, 1930) take into account the screening of the nuclear charge by the inner electrons.

The recoil velocity of ^{7}Be nuclei produced by the ^{4}He(α,n)^{7}Be reaction (see Figure 2) is greater than the orbital velocity of the two electrons of the ^{4}He target atoms. Electron capture into ^{7}Be atomic states during the nuclear reaction is thus improbable and we assumed in good approximation that the ^{7}Be ions are produced fully ionized. As they slow down by atomic collisions, they capture one or more bound electrons and then decay to ^{7}Li. Thus, it produces a γ-ray line at 0.478 MeV, which profile depends on the energy distributions of the ^{7}Be$^{(Z-n)+}$ ions in the region where they propagate.

3.1. ^{7}Be Equilibrium Spectra

In a steady state model, the equilibrium spectra of ^{7}Be ions with n electrons, $N_7^{(n)}$, satisfy a set of coupled differential equations of propagation given by

$$\frac{\partial}{\partial E}(N_7^{(n)}\dot{E}_7^{(n)}) = \sum_j n_j c\beta_7 \big[\sigma_{C;j}^{(n-1)}N_7^{(n-1)} - \sigma_{I;j}^{(n)}N_7^{(n)} + \sigma_{I;j}^{(n+1)}N_7^{(n+1)} - \sigma_{C;j}^{(n)}N_7^{(n)}\big] + \dot{Q}_7^{(n)} - \lambda^{(n)}N_7^{(n)} . \quad (7)$$

Here, $\dot{E}_7^{(n)}$ is the energy loss rate of ^{7}Be$^{(Z-n)+}$; n_j is the number density of species j in the ambient medium; $\sigma_{C;j}^{(n)}$ and $\sigma_{I;j}^{(n)}$ are, respectively, the electron capture (i.e. charge exchange) and ionization cross sections for ^{7}Be ions with n electrons interacting with neutral atoms of type j; $\dot{Q}_7^{(n)}$ is the energy spectrum of ^{7}Be$^{(Z-n)+}$ ions injected into the propagation region (we assumed that $\dot{Q}_7^{(n)} = 0$ for $n > 0$); and $\lambda^{(n)}$ is given by eqs. (3-6). We calculated the charge exchange and ionization cross sections as in Tatischeff et al. (1998).

We solve numerically Equation (7) using fifth-order Runge-Kutta method (Press et al., 1992). Boundary conditions are provided by the assumptions that

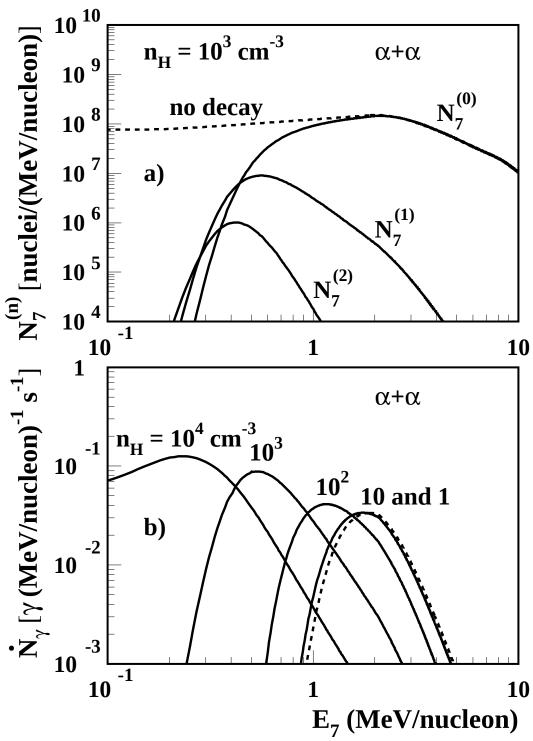

Figure 3. a) ^{7}Be equilibrium spectra in a ambient medium of solar composition and H density n_H=10^3 cm^{-3}, for the differential ^{7}Be production rate shown in Figure 2. The dashed curve shows the equilibrium spectrum of test ^{7}Be^{4+} particles which would not capture electron and decay (Eq. 9). (b) Differential production rates of 0.478 MeV photons from ^{7}Be decay as a function of ^{7}Be kinetic energy, for five values of n_H (dashed curve: $n_H = 1$ cm^{-3}).

at sufficiently high energies (in practice, we used $E_7 > 10$ MeV/nucleon), ^{7}Be ions are fully ionized ($N_7^{(n)} = 0$ for $n > 0$) and both charge exchange and radioactive decay are negligible. Equation (7) then reduces to

$$\frac{\partial}{\partial E}(N_7^{(0)}\dot{E}_7^{(0)}) = \dot{Q}_7^{(0)} \qquad (8)$$

which admits the solution (e.g. Parizot & Lehoucq, 1999)

$$N_7^{(0)}(E_7) = \frac{1}{\dot{E}_7^{(0)}(E_7)}\int_{E_7}^{\infty}\dot{Q}_7^{(0)}(E_7')dE_7' \ . \qquad (9)$$

Calculated equilibrium spectra are shown in Figure 3a for the differential ^{7}Be production rate of Figure 2 and for an ambient hydrogen density of 10^3 cm^{-3}. In that case, ^{7}Be ions decay when possessing one or two bound electrons, as $\lambda^{(2)}$ is significantly greater than the characteristic rate for ^{7}Be^{2+} ions to capture a third electron. For simplicity, we assumed that the ambient medium constituents are atomic species, although such relatively high density is typical of H_2 regions. However, it is a sufficient approximation at this stage, because ^{7}Be ions capture electrons by colliding mainly with ambient He and heavier elements.

3.2. Gamma-Ray Line Emission

The differential γ-ray line production rate following ^{7}Be decay is obtained from

$$\dot{N}_\gamma(E_7) = B\sum_n \lambda^{(n)}N_7^{(n)}(E_7) \ , \qquad (10)$$

where B=10.35 % is the branching ratio to the first excited state of ^{7}Li. The results are shown in Figure 3b for five values of n_H and for the differential ^{7}Be production rate of Figure 2. We see that for $n_H > 10$ cm^{-3}, the differential γ-ray production rate depends on the density of the ^{7}Be propagation region. This is not the case for $n_H \leq 10$ cm^{-3}, because the γ-ray line is then produced by the decay of ^{7}Be^{3+} ions, which do not loose significant energy after having captured one electron.

The energy of emitted photons is related to the kinetic energy of excited ^{7}Li* nuclei, E_{7*}, by the usual Doppler formula. We assumed the γ-ray emission to be isotropic in the ^{7}Li* rest frame and neglected in good approximation the recoil of the ^{7}Li* nuclei during neutrino emission ($E_\nu = 0.384$ MeV), so that $E_{7*} = E_7$. Calculated profiles of the 0.478 MeV line from ^{7}Be decay are shown in Figure 4, together with the prompt γ-ray line emission from the reactions ^{4}He(α,n$\gamma_{0.429}$)^{7}Be and ^{4}He(α,p$\gamma_{0.478}$)^{7}Li. We calculated the latest in the same steady state, thick target interaction model as for the ^{7}Be production (see § 2) and from the total and differential cross sections given in Murphy et al. (1988) and references therein. We assumed the angular distribution of the accelerated α-particles to be isotropic, which leads to relatively broad, prompt γ-ray lines ($\delta E/E = 17$ %). These lines blend to form a broad emission feature (FWHM≃120 keV) with a narrower enhancement at the center. Unlike the prompt emission, the profile of the delayed line at 0.478 MeV depends on the ambient medium density, as ^{7}Be ions decay at lower energies in denser propagation regions. Although the delayed emission accounts for ∼10 % of the total γ-ray line production, we see that the γ-ray spectra are significantly modified for different values of n_H. Thus, the prominent feature at ∼460 keV has a width of ∼50 keV for $n_H = 10^4$ cm^{-3}, against ∼20 keV for $n_H = 10^2$ cm^{-3}. Both SPI and IBIS have potentially sufficient energy resolution to distinguish between these two emissions. Therefore, future fine spectroscopic analyses of the emission profile could in principle allow to better understand the complex interactions of low-energy cosmic-rays with dense molecular clouds.

4. PREDICTED GALACTIC FLUXES

Ramaty et al. (1997) have shown that the observation of the quasi linear correlation between Be and Fe abundances in low metallicity stars implies that the current epoch, Galaxy-wide ^{9}Be production rate is $\dot{Q}(^9\mathrm{Be}) \simeq 3\times10^{39}$ atoms s^{-1}. This result does not

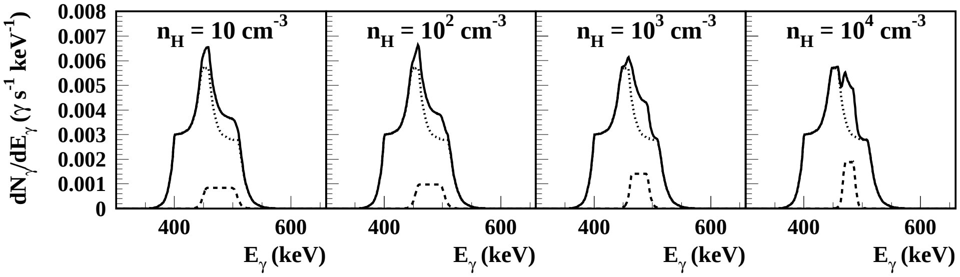

Figure 4. Calculated γ-ray line profiles from α+α reactions in the interstellar medium, including both the prompt lines from the reactions $^4He(\alpha,n\gamma_{0.429})^7Be$ and $^4He(\alpha,p\gamma_{0.478})^7Li$ (dotted curves) and the delayed line at 0.478 MeV from ^7Be decay (dashed curves), for the same α-particle source spectrum as in Figure 2. Solid curves show the sum of the two contributions.

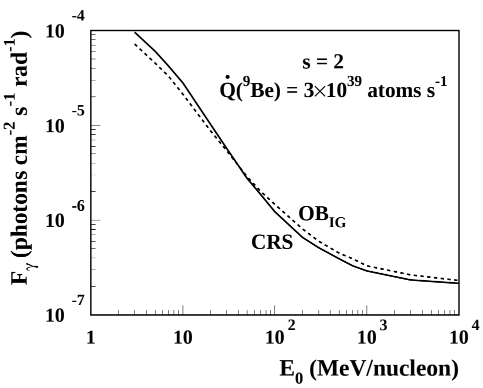

Figure 5. Predicted fluxes of both prompt and delayed γ-ray line emission at ~450 keV from the central radian of the Galaxy. The calculations are normalized to a Galaxy-wide ^9Be production by the fast particles of 3×10^{39} atoms s^{-1} (see text).

depend on the origin of the ^{9}Be-producing cosmic-rays, which is not well understood. Figure 5 shows predicted γ-ray line fluxes at ~450 keV (both prompt and delayed emissions) from the central radian of the Galaxy, assuming that fast particles with CRS or OB$_{\rm IG}$ composition and with source spectrum resulting from strong shock acceleration (Eq. 1 with s=2) are responsible for all the current era ^{9}Be production. We calculated the latest as Ramaty et al. (1997) and also used the same spatial model as these authors. For the prompt γ-ray line emission resulting from the CNO spallation reactions, we simply assumed (given the lack of experimental data) that (i) the productions of excited ^{7}Li and ^{7}Be nuclei are equal and (ii) 10 % of the total ^{7}Be production is accompanied by the decay of its first excited state. This value is based on a recent measurement of the ^{14}N(p,2$\alpha\gamma_{0.429}$)^{7}Be reaction cross section (J. Kiener et al., in preparation).

We see that the predicted γ-ray fluxes strongly increase with decreasing E_0, because of the higher contribution of α+α reactions, which do not produce ^{9}Be nuclei. However, Ramaty et al. (1997) have argued from energetic arguments that the Galaxy-wide ^{9}Be production can not be due to low-energy cosmic-rays with $E_0 < 50$ MeV/nucleon. We thus predict that if ^{7}Li and ^{9}Be are indeed produced by the same cosmic-rays, the ~450 keV nuclear line emission from the central radian of the Galaxy should not exceed $\sim 3 \times 10^{-6}$ photons cm^{-2} s^{-1}. This Galactic background may be difficult to observe with INTEGRAL. However, it does not preclude a possible detection of the ~450 keV line emission from nearby, active regions, such as Cygnus, Vela or Orion.

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